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RESOURCE PRODUCTION ON THE MOON. Geoffrey A. Landis, NASA John Glenn Research Center, 21000 Brookpark Road, Cleveland OH 44135; geoffrey.landis@nasa.gov

Introduction: A self-sustaining settlement on the moon, or on other airless bodies such as asteroids, will require the ability to refine desired raw materials from available resources, such as lunar or asteroidal regolith.

Oxygen is the highest value resource to be produced [1,2], since it is the main (by mass) component of rocket fuel, and hence fuels a critical transportation need, as well as serving as a possible commercial product for use in other space systems and to expand settlement to other locations. Breathable oxygen is also a necessary product for life support. Thus, oxygen will undoubtedly be the first product to be refined. However, it will also be desirable to refine raw materials for other purposes, including structural materials and materials for industrial applications, such as production of solar arrays [3]. The most desirable processing sequence therefore would focus on an initial goal of oxygen production, but using a technique that could be expanded to produce and refine other raw materials.

This work will focus on the example case of production from lunar regolith [1-3]. The same process sequences could be used at other locations. Stony asteroids typically have regolith similar to that of the moon, and refining of asteroidal material could use the same techniques, adapted for microgravity. (Other types of asteroids would allow processing possibilities not considered here. For example, Type-C asteroids contain carbon and can contain some amount of chemically bound water, which can be used for different purposes. Metallic asteroids can be processed to produce both bulk and previous metals.) Likewise, Martian rock and soil could also be processed by the techniques discussed here.

Processing

Desired Materials. Other than oxygen, the following materials are valuable.

1. Metals. Metals are a ubiquitous structural material, and will certainly be used in lunar manufacturing. Structural metals include iron and steel, aluminum, and titanium. Each of these are of value for different uses. All of these are available as elemental components of lunar material. Metals are also used as wires conductors. From its elemental abundance in lunar soil and high electrical conductivity, aluminum is the clear choice for wires. A second possible choice is calcium, not used on Earth because of high reactivity with oxygen, but a possible conductor for vacuum applications.

2. Glass and ceramics. Transparent glass is a required material in forming solar arrays [3]. Ceramics are also useful as insulators. Glass or ceramic fibers are also useful for structural composite materials.

The primary glass-forming material, silicon oxide, is abundant on the moon, in the form of silicates. Transparency will require refining, most particularly to remove trace amounts of iron and other transition-metal oxides, which produce color centers that turn glass dark. Usable glass is not merely silicon oxide, but an engineered material with many components selected to produce the required properties. Several of the oxides which are used to adjust the properties of glass are not abundant on the moon. Na_2O, the main component of "soda lime glass", is typically used to reduce the melting point, allowing easier working. B_2O_5, to produce borosilicate glass, is typically used to adjust the thermal expansion coefficient. New glass compositions will have to be invented to reduce, or eliminate, the amounts of these materials that are rare in lunar soil.

3. Silicon. One of the most important issues for settlement is production of power. Many different semiconductors can be used to produce photovoltaic cells, but from the standpoint of lunar abundance of materials, the clear choice for locally-manufactured cells is silicon solar cells. Silicon suitable for semiconductor applications is a highly purified product; parts per billion of some impurities is sufficient to degrade the properties. Thus, a processing sequence for making solar-cell grade silicon must include purification steps.

4. Civil-engineering materials. In addition to structural materials, lunar settlements will undoubtedly require less highly processed material. Although habitation structures on the moon will not be made of ordinary bricks (since habitats must hold pressure, and hence will be tension structures), there will still be the need for the equivalent of concrete, asphalt, and bricks. Many possibilities for such bulk material exist, including sintered or melted regolith bricks, material produced from slag from other processes, or composite materials comprising aggregate fill cemented with a ceramic matrix.

Processing Overview. A processing sequence can be broken into three main steps:

(1) acquisition and beneficiation (if required) of feedstock

(2) Reduction

(3) Refining of the desired raw materials and purification to the required level

The current work will focus primarily on the second step, reduction.

The acquisition portion of the processing is a sequence of prospecting (if required), materials acquisition and mining, grinding or otherwise preparing the material for processing, and (for some sequences) beneficiation of the input material to increase the concentration of the desired mineral. Preferably, the sequence selected could be fed from regolith which is available at any lunar location, minimizing and possibly eliminating the need for prospecting and for beneficiation.

The reduction step comprises stripping the oxygen away from oxides. This step produces the main product, oxygen. Lunar regolith is primarily silicates, in which the oxides are in the form of oxygen bridging between silicon atoms, chemically bonded to metal cations in a strongly-bound net. The reduction process therefore requires breaking the silicon-oxygen bonds.

After the oxygen is produced, the byproduct is reduced (or partially-reduced) metals. The resultant product may be a mixture of metals. To turn this into useable raw material, the desired materials must be separated and purified to the levels needed.

Magma Electrolysis: Magma electrolysis is conceptually the simplest method of refining regolith into reduced metals and oxygen. It consists of heating lunar soil to the melting point, then running electrical current through the melt to electrolyze the anions (primarily oxygen) at one electrode, and the cations (metals and Si) at the other [4]. However, the details are complicated. A significant difficulty is the extremely high temperatures needed, from 1300 °C to 1450 °C, which result in significant practical difficulties.

Calcium Process: The calcium process [5] is chosen as a method of reducing the temperatures needed. This process requires considerably lower temperatures than direct Magma electrolysis, and produces oxygen with considerably higher efficiency than hydrogen or carbothermal reduction methods.

The process has of two steps: reducing the regolith, and then regenerating the metallic reactant:

(1) Calciothermic reduction. This is done by heating of the regolith in the presence of metallic calcium, to convert the silicates into metals plus calcium oxide.

(2) Electrolysis: this stage electrolyzes the calcium oxide in a molten salt at 825-900 °C, to produce metallic calcium and oxygen.

Metallothermic reaction: The metallothermic reduction has been used for production of metals on Earth, including rare-earth elements, manganese, chromium, vanadium, zirconium, and niobium.

Regolith is heated with metallic calcium at a temperature greater than the melting point of calcium, 845°C. The reaction rate is enhanced by use of finely-ground reactants as well as an excess of calcium. An typical reaction equation is:

$MgFeSiO_4 + 4Ca \rightarrow 4\ CaO + MgFeSi$

Since calcium and calcium oxide are soluble in calcium chloride, $CaCl_2$ or a $CaO/CaCl_2$ eutectic mix can be used as a flux to accomplish the calciothermic reaction in a liquid solution. The reaction byproduct comprises the reduced metals and silicon. The molten byproduct is denser than the oxide or the reactant, and settles to the bottom of the crucible as a liquid. Further separation and purification steps can be taken from this point to produce refined product for other processing.

Molten Salt Electrolysis: Following the reaction, the oxygen is entirely bound in the reaction product, calcium oxide. To generate oxygen (and recover the reactant, elemental calcium), this oxide is electrolyzed:

$Ca^{+2} + 2\ e^- \rightarrow Ca$ (metal)

$O^{-2} \rightarrow \frac{1}{2} O_2 + 2\ e^-$

net: $CaO \rightarrow Ca$ (metal) $+ \frac{1}{2} O_2$ (gas)

The electrolysis is done in a molten calcium chloride/calcium oxide mixture, with a eutectic point of 750 °C.

Fluorine Process: The process uses reaction with fluorine to displace the oxygen from the rock, producing fluorides, followed by potassium displacement to produce KF, which is electrolyzed [3,6].

The basic reduction process is to heat the regolith in the presence of fluorine. The fluorine displaces oxygen (collected as a useful product). Silicon and titanium produce volatile fluorides, SiF_4 and TiF_4, both gaseous at the processing temperature. The tetrafluorosilane can be easily purified to semiconductor-grade by distillation. The remaining metals are produced in the form of fluoride salts, which must be reduced to the metals. The iron and aluminum fluorine salts are directly reduced with potassium:

$FeF_3 + 3K \dashrightarrow 3KF + Fe$

$AlF_3 + 3K \dashrightarrow 3KF + Al$

Calcium and magnesium fluorides are not reduced by potassium, and are returned to oxide form by potassium substitution:

$CaF_2 + K_2O \dashrightarrow 2KF + CaO$

$MgF_2 + K_2O \dashrightarrow 2KF + MgO$

The oxides are then available for glassmaking. The reactants, fluorine and potassium, are returned in the form of KF, and are then recovered by electrolysis in a potassium/sodium/calcium fluoride eutectic at 676 °C.

References: [1] J. Lewis, M. S. Matthews & M. L. Guerrieri (1993), in *Resources of Near-Earth Space*, U. Arizona Press, pp. 17-448. [2] G. B. Sanders, *et al.* (2008), AIAA-2008-7853, *2008 AIAA Space Conference*, San Diego CA. [3] G. A. Landis (2005), *NASA TM-214014*. [4] E. D. McCullough and A. H. Cutler (2001), AIAA-2001-0938, *39th AIAA Aerospace Sciences Meeting*, Reno NV. [5] G. A. Landis (2011), AIAA-2011-701, 49th *AIAA Aerospace Sciences Meeting*, Orlando FL. [5] G. A. Landis (2007), *Acta Astronautica, 60*, 10-11, pp. 906-915.